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REPORT SSD-TR-90-015

AD-A220 492

Implications of Cloud Obscuration on Ground-Based Laser Systems for Strategic Defense

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12 March 1990

Prepared for

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This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-88-C-0089 with the Space Systems Division, P.O. Box 92960, Los Angeles, CA 90009-2960. It was reviewed and approved for The Aerospace Corporation by J. R. Stevens, Principal Director, Defense and Surveillance Operations. Col. J. Williams, SSD/CN was the Air Force project officer.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
TR-0090(5017-03)-1

5. MONITORING ORGANIZATION REPORT NUMBER(S)
SSD-TR-90-015

6a. NAME OF PERFORMING ORGANIZATION
The Aerospace Corporation
Programs Group

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
Space Systems Division
Air Force Systems Command

6c. ADDRESS (City, State, and ZIP Code)
2350 E. El Segundo Blvd.
El Segundo, CA 90245

7b. ADDRESS (City, State, and ZIP Code)
Los Angeles Air Force Base
P. O. Box 92960
Los Angeles, CA 90009-2960

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
F04701-88-C-0089

8c. ADDRESS (City, State, and ZIP Code)

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
(U) IMPLICATIONS OF CLOUD OBSCURATION ON GROUND-BASED LASER SYSTEMS FOR STRATEGIC DEFENSE

12. PERSONAL AUTHOR(S)
Michael T. Tavis, Capt. Scott W. Levinson, Lt. Kathryn M. Parker

13a. TYPE OF REPORT

13b. TIME COVERED FROM ________ TO ________

14. DATE OF REPORT (Year, Month, Day)
1990, March, 12

15. PAGE COUNT
24

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Ground-Based Laser
Cloud-free arc
Cloud-free line-of-sight

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The evolution and the current status of the Strategic Defense System Phase II Ground-Based Laser (GBL) System Concept is reviewed in this report. In particular, the impact of clouds on system configuration and site selection is discussed. By using current models of correlated probabilities of cloud-free line of sight and cloud-free arc (CFLOS4D and CFARC) for several ground stations with cloud realizations provided by the Boehm Saw Tooth generator, we have determined the number of ground sites required to achieve various levels of desired system weather availability. We briefly described potential improvements in the models and discussed the necessity for using the Whole Sky Imager results now being generated to validate these models with empirical data, thereby lending further credibility to GBL System Concepts.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE (Include Area Code)

22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

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I. INTRODUCTION

In 1985 the Strategic Defense Initiative's chief scientist, G. Yonas, was reported in the L. A. Times newspaper as suggesting that clouds could be a possible program stopper for the Ground-Based Laser (GBL). The rationale for such a statement was that optically thick clouds are present over 30 to 70 percent of the earth and that they are correlated in space and time. Further, high altitude sites, which are more favored by GBL systems since they reduce adaptive optics requirements, may have more severe cloud cover. High power GBL weapons would have little or no capability in the presence of such clouds. Solutions to this problem include site proliferation and creating a hole in the cloud cover. It was recognized that clearing a hole in thick clouds was probably not practical and, therefore, clearing would be an adjunct to proliferation in that it might reduce the absentee ratio. At that time it was believed that an absentee ratio greater than about six would make the GBL system prohibitively expensive when compared with the Space-Based Laser (SBL). However, data and modeling capability were insufficient to determine the required number of sites and hole clearing requirements. An SDI/Cloud Workshop was held in September 1985 at the Institute for Defense Analysis to discuss these issues. At that time the Directed Energy Weapon (DEW) program office at the Air Force Space Systems Division (AFSSD) had three parallel analysis efforts in place to develop GBL System Concepts. Siting was a major factor in the initial concept formulation, and these study contractors attended the workshop. Their work up to that time had been based mostly on the assumption of uncorrelated sites with high probabilities of cloud-free line of sight (PCFLOS). At the workshop there was general agreement that, with a CONUS representative PCFLOS of 0.6, a system availability of not more than one predictable cloud-induced outage of more than 3-hr duration per year could be achieved with between 5 to 15 independent ground stations. It was recognized that this wide variation in required ground stations was unacceptable and called for meteorological research to enhance the database and increase confidence in the system constructs. Further modeling efforts were needed to better define the required number of ground sites. It was also recognized that cloud clearing physics and associated thermal blooming and turbulence were not well understood. Theory was incomplete and not trusted

without experimental verification. Finally, the use of cloud clearing could not be assessed without better information on the occurrence of thin and cirrus clouds that are more amenable to clearing. These uncertainties led to the initiation of the Whole Sky Imager program, experiments on cloud clearing and quantification of induced optical path disturbances, and modeling efforts for multisite cloud-free line of sight (CFLOS4D) and cloud-free arc (CFARC).

Cloud analysis has played a critical role in the system concept definition process. Based on required levels of cloud-free system availability, the accuracy of modeling (which determine the number of required ground sites necessary to achieve this availability), and the current and achievable levels of technology, the DEW elements are designed to meet the mission requirements at minimum cost. In this report the impact of clouds on the system concept for the GBL is discussed. We start by defining the role the DEW systems analysis has in the overall Strategic Defense Systems (SDS). The evolution and current status of the GBL system is detailed. Particular attention is paid to the role that clouds have played in system design, showing the synergism that exists between ground site selection and space asset constellation. The system configuration will then be shown, and results for the required number of ground sites generated by CFLOS4D will be discussed. We describe possible improvements to the models and discuss the impact that Whole Sky Imager data will have on validating and improving the multisite CFLOS models. Finally, the system implications of cloud hole boring will be discussed.

II. BACKGROUND

The DEW System Program Office (SPO) at AFSSD coordinates Air Force efforts in the SDIO technology base. It is also our responsibility, with co-management by the Army, to synthesize GBL weapon element designs based on the best assessments of achievable technology capable of meeting mission requirements as developed by the system architects. In general, the less risky technology approach is preferred unless a substantial cost advantage or mission requirement dictates following a higher risk path. We also specify subsystem requirements and designs to clarify technology development plans and provide detailed System Concepts back to the architects for inter-element trades. These system concepts are periodically updated to reflect the changing defense policy as manifested by the needs of the architects as well as advances in technology.

There are many elements in the design of a GBL system. These elements interact in a complex fashion making it very difficult to design the entire system in an optimum manner. One technique is to apply a consistent global figure of merit. Since the GBL system has significant assets in space as well as on the ground, the most appropriate figure of merit for GBL systems is investment cost. Whereas detailed cost analyses are not explicitly discussed here, the rationale for critical decisions used in progressing through a concept decision tree are presented.

First we present the evolution of the GBL system (Figure 1). In 1985, the architects desired a far-term DEW system capable of destroying in boost nearly all of a massive, laser hard fast-burn booster, spike-launched threat. Excimer and free electron lasers (FEL) were examined. Free electron lasers were selected in a globally based construct at weather independent sites having extremely high PCFLOS. Surprisingly, the selection of globally dispersed basing has a profound impact on the space constellation design. Specifically, since the laser sites would be geographically dispersed, the optimal space constellation most consistent with this basing scheme uses a single type of satellite in a circular mid-earth orbit (MEO) that fulfills the role of both relay and mission mirrors. Only one or two lasers would be based

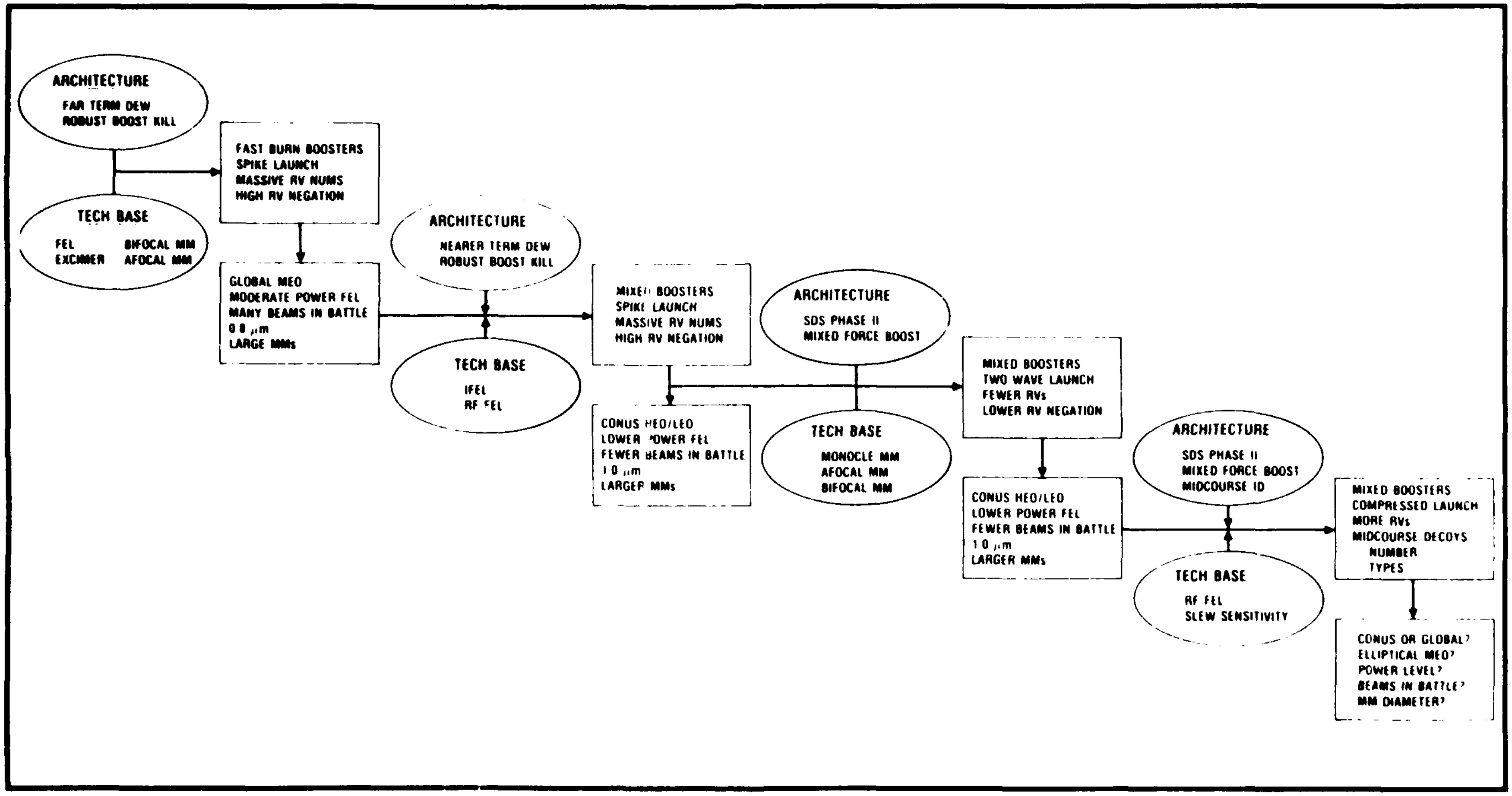

Figure 1. GBL System Evolution. The GBL concept has evolved from a far-term robust boost phase weapon to a nearer term concept based on achievable technology.

at each site. In 1987, SDIO directed that a nearer term system still capable of destroying nearly all missiles of a spike launch, but of an earlier generation ICBM, should be designed. A policy decision was also made that only CONUS basing was acceptable in this time frame. This design input was a key driver that led to a baseline concept of lower power FELs clustered at multiple sites and a space constellation consisting of high altitude Molniya orbit (HEO) relay mirrors dwelling over laser sites and mission mirrors in low earth circular orbits (LEO). Eight ground sites were used to achieve a high percentage of cloud-free availability, six located in the Western United States and two in the Eastern United States. This separation was needed to enhance decorrelation of large weather patterns. Since then, the basic system configuration has not changed significantly, although the number of beams in battle, the number of ground sites, and some technology features have changed to meet the evolving needs of the architects as threats have varied and other weapon elements have been introduced into the battle.

Figure 2 recaps the evolution of cloud impact on the GBL system. In the Introduction we discussed the DEO request for more information on how clouds would impact the system and the cloud workshop at IDA. Previous experimental efforts included CLEAR I, II, and III that initially included cloud measurements as well as turbulence characterization at given sites. Due to funding limitations, the cloud measurements were curtailed. Strategic Defense Initiative Organization direction of CONUS basing led to the current site requirements that were determined by the Concept Formulation and Technology Development Programs (CF&TDP) and the use of the CFLOS4D and CFARC models using cloud realizations provided by the Boehm Sawtooth generator. The use of the Whole Sky Imager data in model verification will be discussed later.

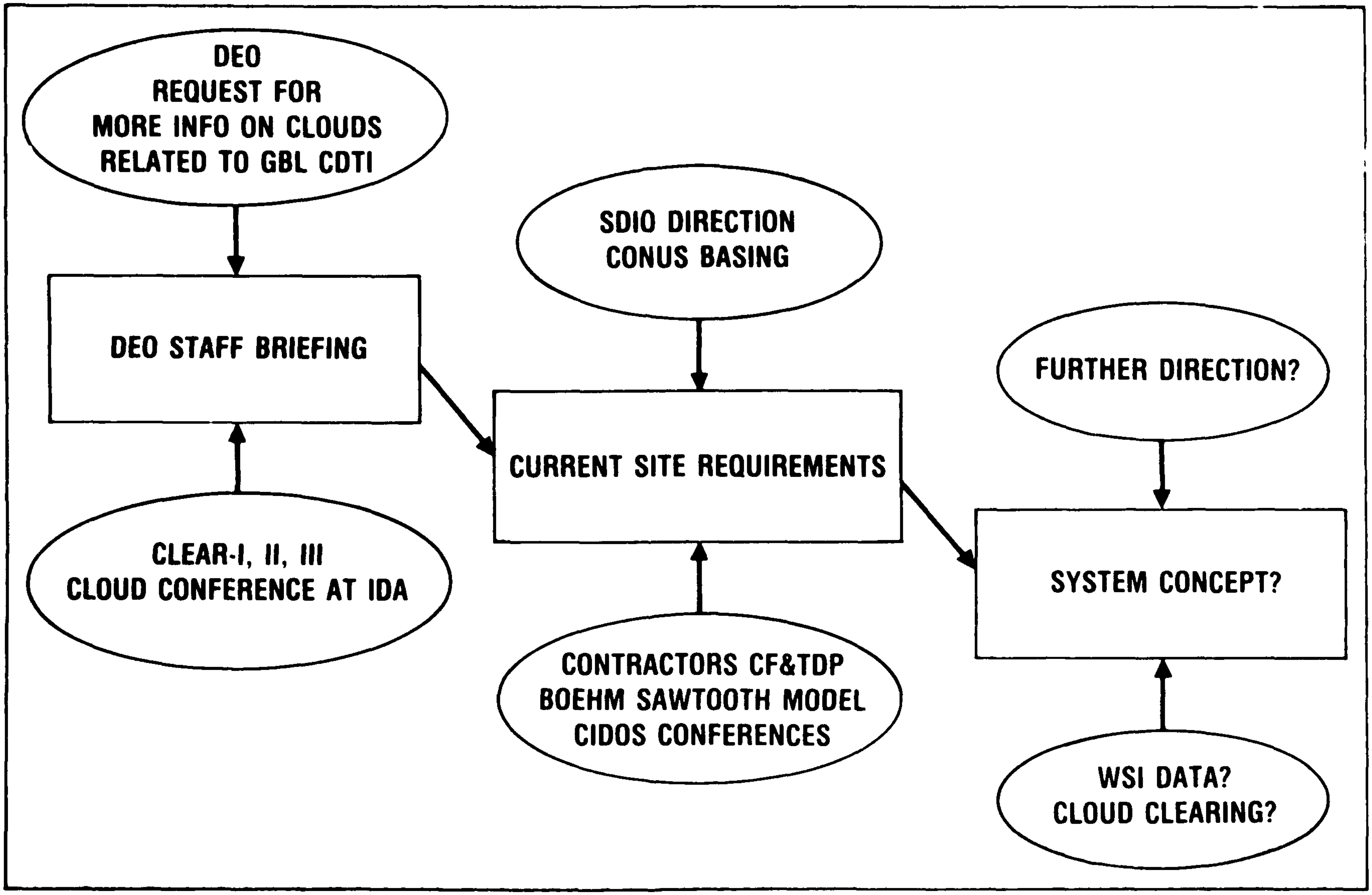

Figure 2. Evolution of GBL Cloud-Impact Analysis

III. GROUND-BASED LASER SYSTEM ANALYSIS

To meet SDI mission requirements, the GBL system must be both lethal and available to fight the war with a high degree of certainty, irrespective of clouds. Figure 3 shows the trades available for lethality and availability. The lethality of a laser beam is generally greater for higher powered beams, and it has been found that the costing methodology favors fewer higher power beams in order to fight the battle; however, we have seen that the cost minimum is generally shallow. There are also many technical risks associated with the high power branch. Retargeting timelines are stressing, and there are problems associated with thermal blooming and simulated raman scattering (SRS) that are exacerbated on that branch. For these reasons, the many lower power beam branch is preferred for present missions. Even though our current system specifies a fewer number of beams, we are still considered to be on that branch, and updates are underway to reoptimize the system constructs based on updated threats and missions. Availability in this report means the absence of cloud blockage. The probability of clearing thick clouds has already been dismissed so some level of avoidance is necessary in any case, and is considered as the trade branch selected for more detailed analysis, and in fact has been the basis of our concept development to date. There are still many issues related to avoidance such as the scarcity of data, especially for correlated PCFLOS and model verification. Recent studies of correlated sunshine data[1] have increased our confidence in current models somewhat, and we discuss them again later in this report. There are also many systems issues related to cloud clearing such as power requirements, system cost, the residual turbulence left after or induced by clearing, cloud recondensation, and the possible offensive uncertainties introduced by the implementation of cloud clearing lasers. We have not studied these issues in our detailed concept studies, but these issues have been considered more fully in papers presented at the Cloud Impacts on DoD Operations and Systems 1989-1990 Conference (CIDOS 89/90). However, we may cost such systems in our CF&TDP studies in the near future with the prospect of reducing the required number of ground sites if it is cost effective.

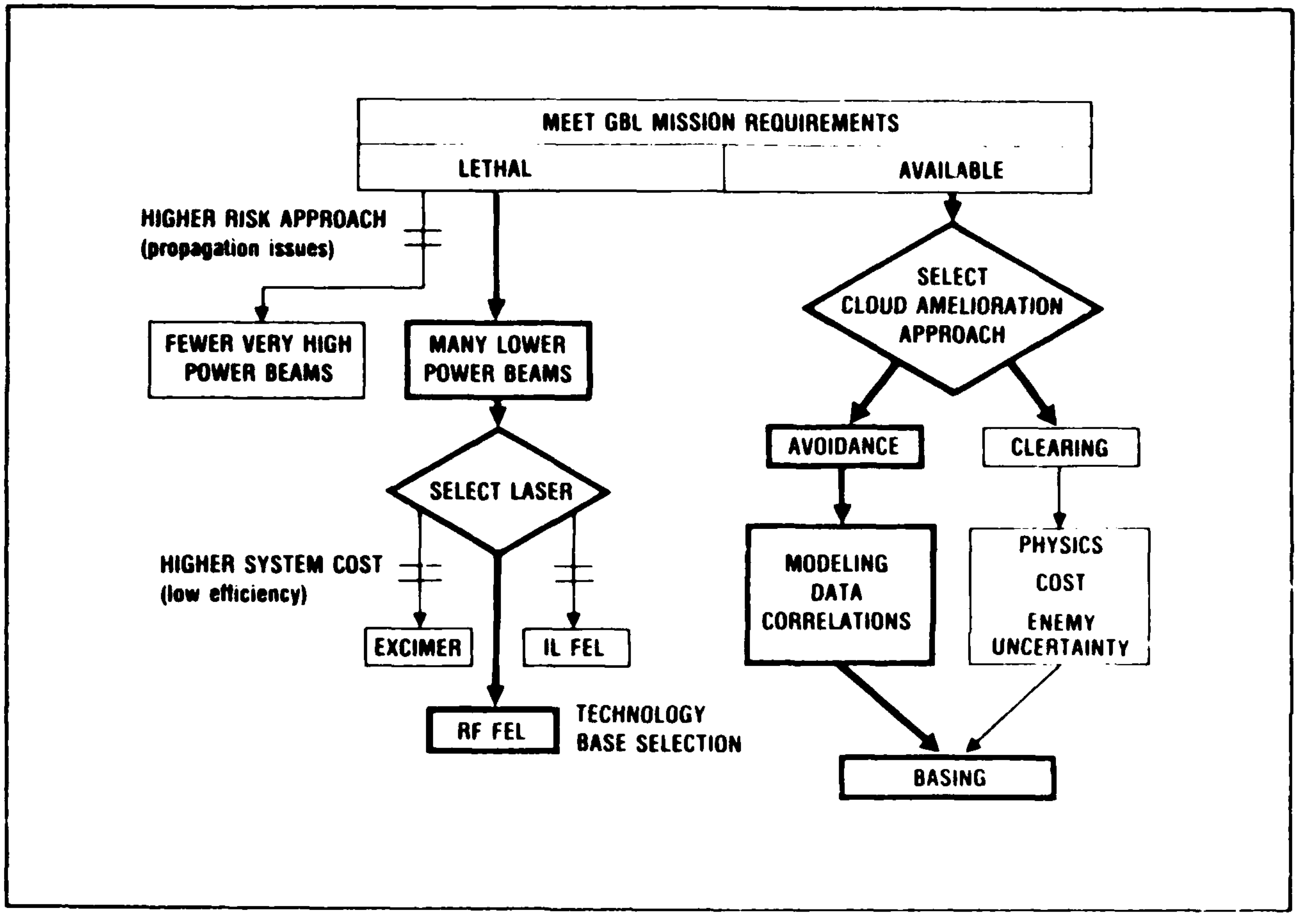

Figure 3. GBL Concept Definition Trade Space - Lethality and Availability

Figure 4 highlights the trades associated with the ground site basing and the space constellation associated with the selected basing mode. As stated previously, cost is our figure of merit, and the optimal system from a cost perspective is globally based. This option allows the system designer to select sites with extremely high PCFLOS or CFARC, thereby reducing the absentee ratio. If the sites are weather independent, then it can be shown that the least number of lasers are required if only one laser is situated at each site. As a simple example if one considers the case that each site has the same PCFLOS (P), then the total number of sites (N) required is determined by the probability of having at least M clear sites out of N total sites $P_N(M)$ greater than a given required system availability (P_A). Then

$$P_A \leq P_N(M) = 1 - \sum P^i(1 - P)^{N-i} N!/(i!(N - i)!) \quad \text{for } i = 0 \text{ to } M - 1.$$

By plotting the total number of lasers required (the total number of sites times the number of lasers per site) versus the number of lasers per site (L) for a given P_A and number of beams in the battle (B), a minimum occurs at one laser per site. The required number of clear sites is the first integer greater than or equal to B/L whereas N is the smallest integer that satisfies the above equation. For the all-MEO space constellation, one finds that the number of satellites is driven by the requirement to provide uplink coverage for each of the individual ground stations. The GBL Concept Definition studies have shown that this combination of ground basing and space constellation is less expensive than clustered basing and HEO/LEO combination since fewer lasers and space assets are required. The studies have also shown that only one type of large space asset is required, the bifocal mirror satellite. Further advantages include graceful system degradation as space or ground assets are lost, and improved performance as more ground sites become clear. If CONUS basing is selected due to policy constraints, then orbit selection is nearly a foregone conclusion. It is necessary to provide relays accessible to ground bases spread over a small region when compared to world-wide basing. The presence ratio of MEO satellites is so small that the number of MEO satellites needed for uplink coverage would be prohibitively large. Therefore, the best choice is a high altitude, highly elliptical Molniya orbit (63 deg inclination) that loiters over the Northern Hemisphere

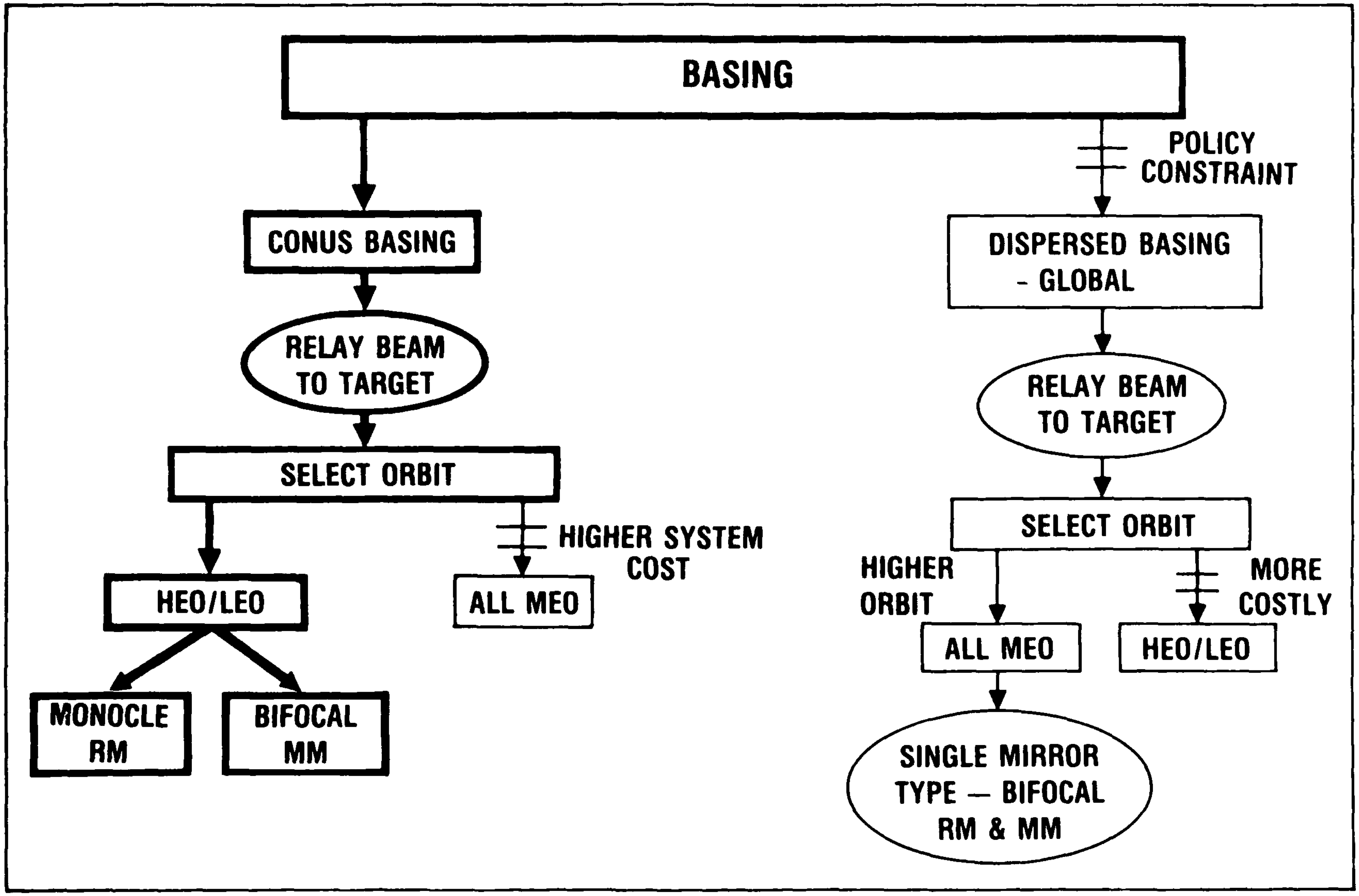

Figure 4. GBL Concept Definition Trade Space - Basing and Satellite Options

and is accessible by all ground stations in CONUS. Geostationary orbits are not acceptable, since it generally takes an additional relay for the beam to reach the mission mirror. Two relays are needed since geostationary orbits are at the equator whereas the entire battle is occurring over the pole in the far Northern Hemisphere. The bifocal mission mirrors are in a lower altitude in this configuration where they more efficiently fight the boost phase battle. This efficiency is driven primarily by diffraction considerations that increase the spot size on target as a function of $(\text{Range})^2$. Ground sites in the Southwest are preferred since the PCFLOS is greater; however, the probability of correlated weather effects becomes quite large there. This means that the number of lasers required to perform the mission must be greater than if the sites were widely separated. This is demonstrated in Figure 5 where the CONUS curve has a greater slope than the global case. It now becomes critical to have an accurate modeling capability and a very good data base from which the correlated PCFLOS for multiple ground sites can be determined. Errors in this estimation are crucial since proliferation of ground sites is not as effective due to weather correlation and multiple lasers are placed at each site. The loss of even one expected ground site due to clouds causes a significant mission effectiveness reduction. To reduce system cost, the number of relays available is limited to that needed for nominal performance levels. Therefore, additional clear sites will not improve performance.

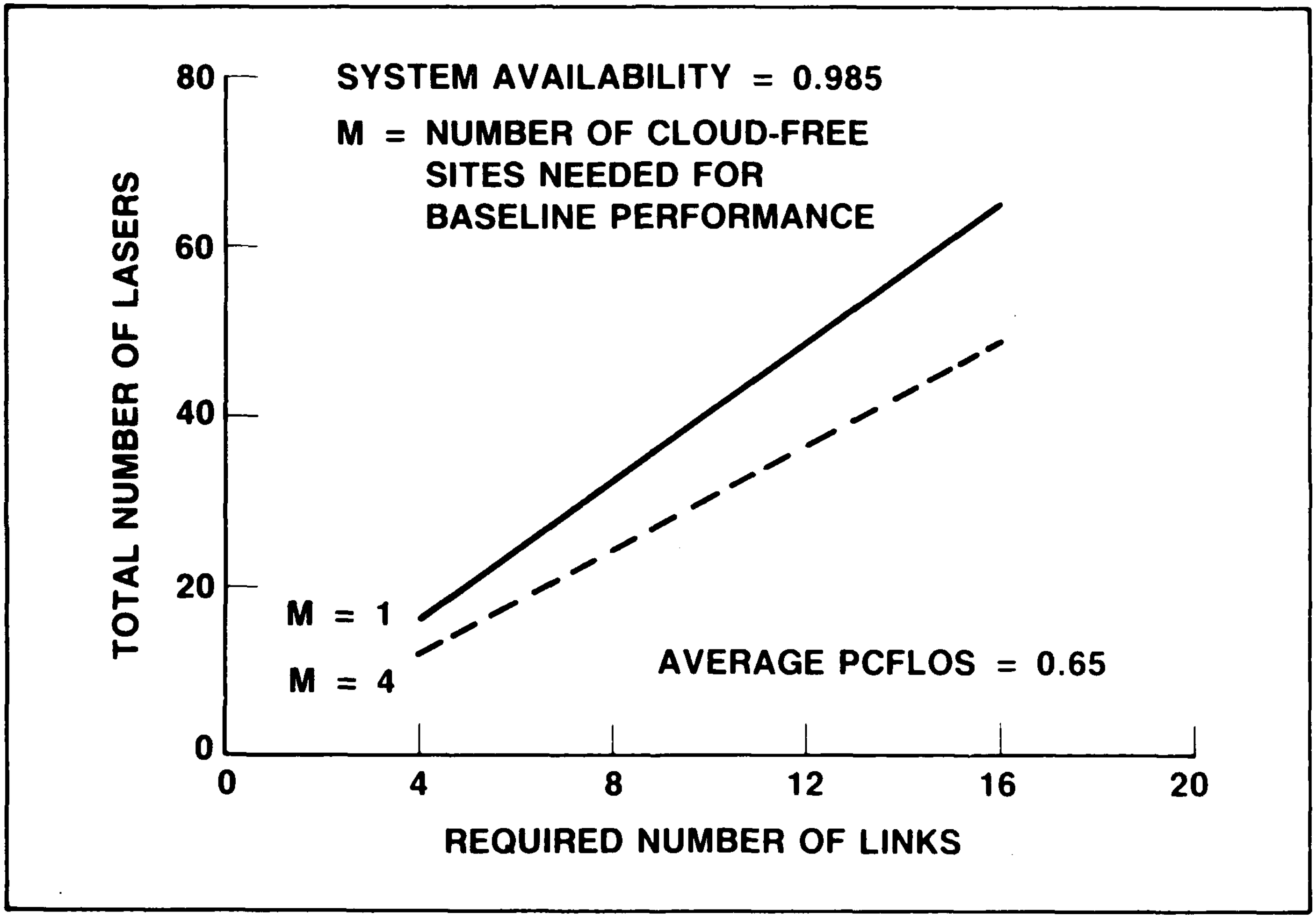

Figure 5. Laser Requirements for Global/CONUS Basing

IV. GROUND-BASED LASER SYSTEM DESCRIPTION AND REQUIREMENT

The GBL system concept shown in Figure 6 uses free electron lasers (FEL) operating at 1.06 μm. The RF FEL has been selected by the United States Army Strategic Defense Command (USASDC) for further development. The system is designed to destroy in boost and postboost phase a substantial percentage of a compressed launch of the 2008 threat described in the 1989 Strategic Threat Assessment Report (STAR). There are four ground stations of which three are located in the Southwest and one is located in Florida. Each site has multiple lasers each powered by a suite of diesel generators. Turbulence and thermal blooming conpensation is provided by a conventional, phase only, adaptive optics system with a beam director smaller than the Keck telescope. The reference wavefront required for adaptive optics correction is generated at a beacon satellite accompanying the relay mirror but at the correct lead ahead distance to account for round trip delay.

The monocle relay mirrors are in a 12-hr Molniya orbit (critically inclined at 63 deg) with an apogee of 39000 km and a perigee of 2000 km. This allows approximately 8-hr access to each mirror. Wavefront correction is provided by edge actuation while the error is determined by grazing incidence interferometry. Absolute segment phase could also employ the same techniques although several wavelengths would be employed. The high power laser beams are relayed to bifocal mission mirrors. The input aperture is large enough to collect between 70 and 85 percent of the relayed energy. A portion of the outgoing wavefront, sampled by holographic elements applied to the primary, is used to determine the phase corrections needed to correct for thermal and jitter errors introduced into the beam in the bifocal. These mission mirrors are in a low-earth circular orbit that is highly inclined. The mirror weights and dimensions are well within the constraints set by the Advanced Launch System (ALS). Finally, the overall optical efficiency from laser to output of the mission mirror is approximately 20 percent.

As stated above, four ground sites were chosen for the GBL system. We used CFLOS4D to determine the number of ground sites needed to achieve a probability of system availability of 98.5 percent or greater of having one or

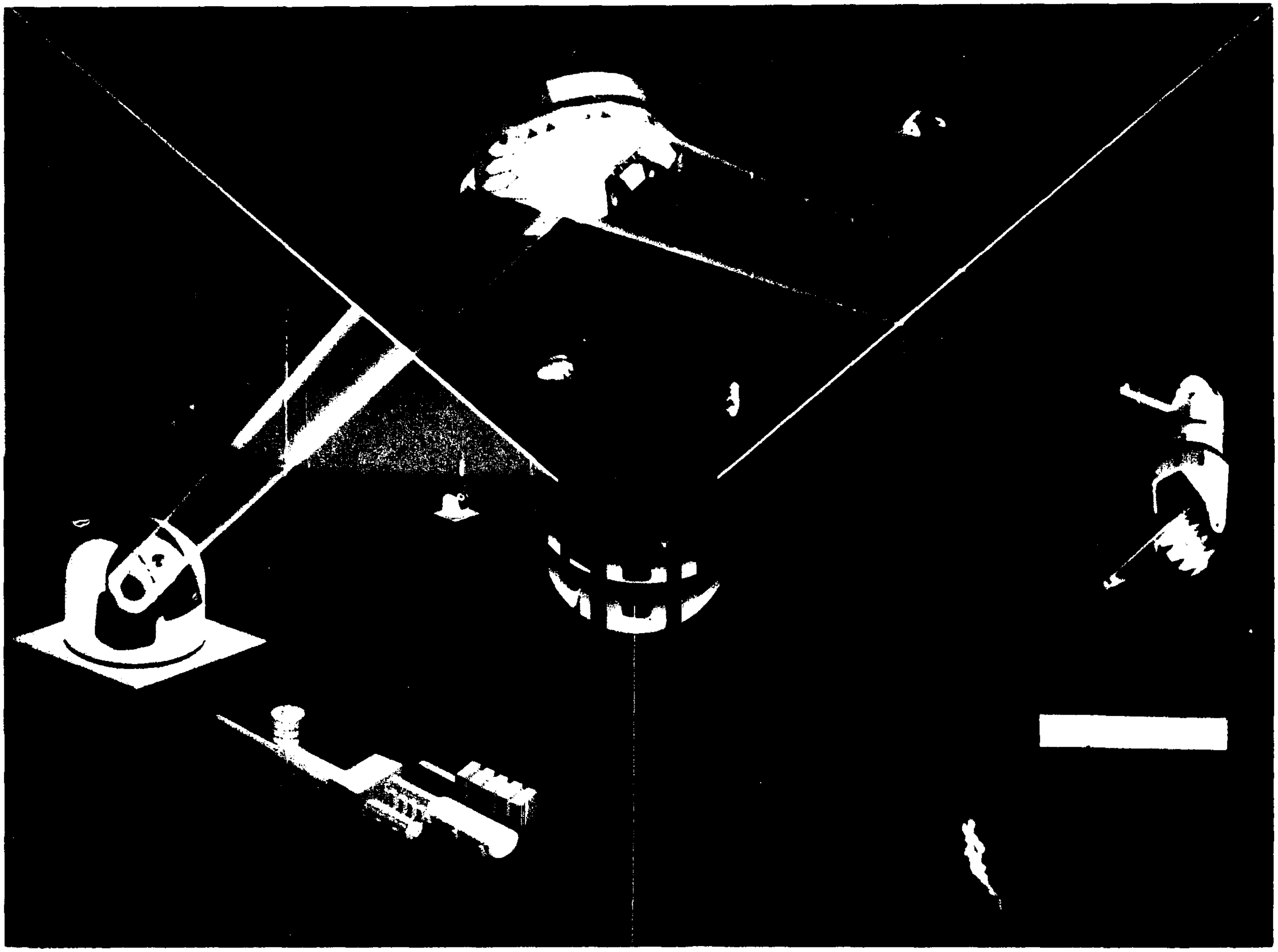

Figure 6. GBL System Concept. High power laser beams generated on the ground are relayed to the mission mirrors by High Earth Orbit Monocles. The Bifocal Mission Mirrors focus the beams on the target.

more ground sites clear. More importantly, two or fewer 3-hr outages per year are estimated to occur, reducing the potential for enemy exploitation of long duration outages. The results are shown in Figure 7. As shown, the number of system outages of less than 3 hr is fairly large; however, prevailing judgement suggests that only outages of 3 or more hours are predictable and thus exploitable. Florida was selected for one site (No. 3). This site was selected to provide decorrelation with the weather patterns in the Southwest.

Previous studies that included four extra bases at Yuma, Arizona; Nellis Air Force Base, Nevada; Casper, Wyoming; and Loring, Maine have indicated greater than 99 percent system availability for two or more sites out of eight and approximately one time per year of a system outage of greater than 1/2 hr.

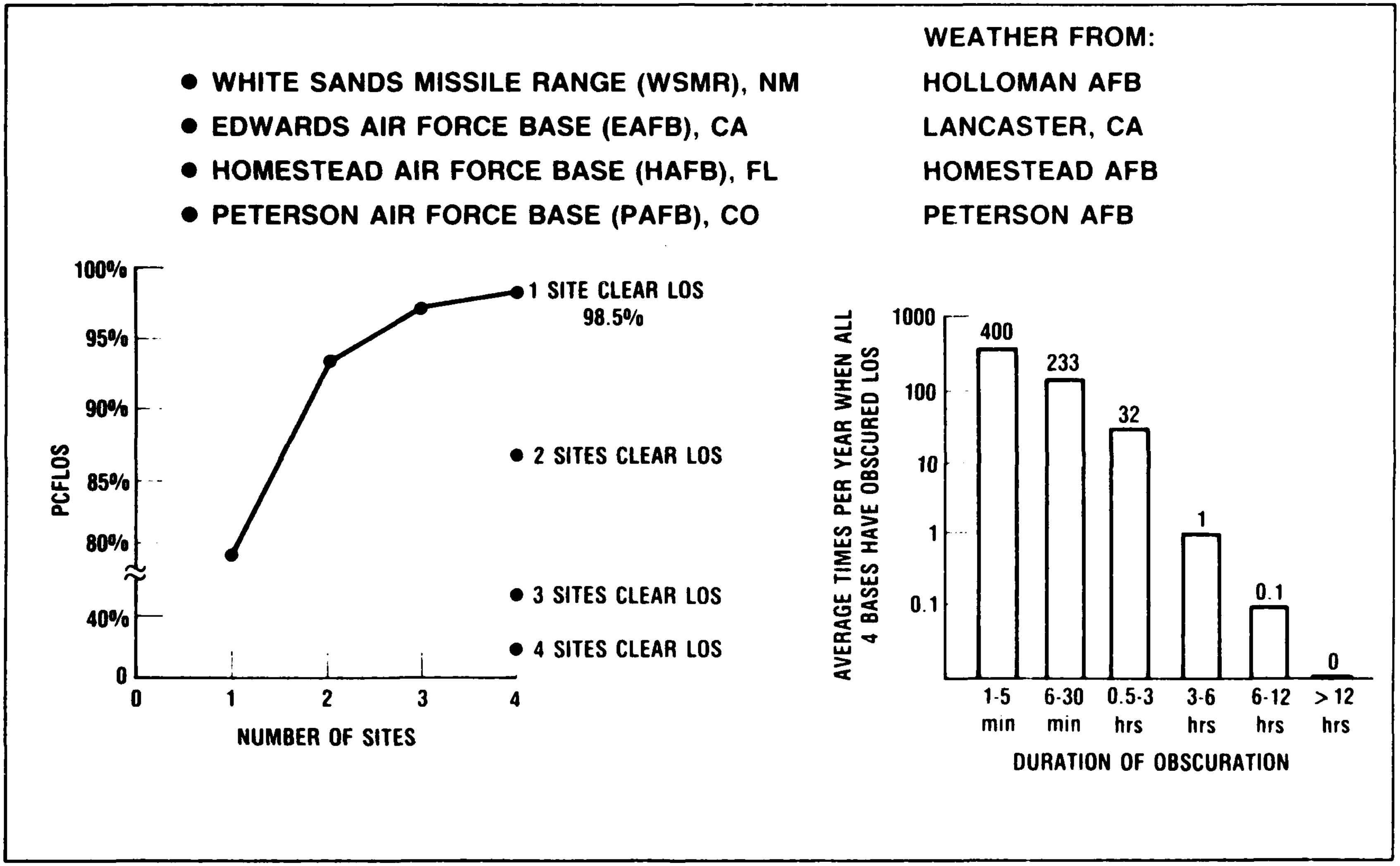

Figure 7. Site Requirements. The probability of cloud-free line-of-sight to the relay mirrors is required to be greater than 98.5 percent.

V. MODELING

Two simulation models were developed at the Air Force Geophysics Laboratory and the USAF Environmental Technical Applications Center to calculate cloud-free line-of-sight for multiple weather correlated ground sites.[2] The CFLOS simulations provide cloud-free line-of-site or cloud-free-arc and downtime statistics for systems of one or multiple sites that are weather correlated in time and space. The long spatial correlation function is based on sky cover correlations between pairs of stations modified by Lund's CFLOS algorithm.[2] The correlation is a function of geographic location and time of year. The Lund assumption states that the conditional probability of CFLOS at one station is independent of the other since the arrangement of clouds over the separated sites should be independent. At very short site separations this assumption is invalid, and Burger added an additional spatial correlation to account for short distances. This correlation is based on sky dome cloud cover. Time correlation was modeled using hourly whole-sky photos of cloud cover at various Midwest sites. Line-of-sight relaxation observations were only made at Columbia, Missouri and included both hourly and 5-min photos. A 4-dimensional sawtooth is used to simulate cloud covers. The program generates 14 sawtooth waves of random orientation and phase. Seven of the waves are of long temporal wavelength and seven are short. The use of seven harmonically related waves simulates the exponential fall off with time, i.e.,

$$\rho(\Delta t) = \exp(\Delta t/\tau)$$

of the temporal correlation of cloud cover at each site. The direction of the waves is represented in terms of direction cosines and the equation of a time/space hyperplane in which the wave phase is constant. Direction cosines are chosen such that any direction is equally probable and all points remain within a hypersphere, i.e., points between the sphere and circumscribed cube are rejected. The correlated normally distributed sums of N sawtooth wave heights are then compared to a threshold. This threshold is the normal deviate that corresponds to the climatological probability that a cloud will obscure the line of sight. Details of this calculation and the choice of sawtooth wavelengths are given in Ref. 2.

The climatological data base for determination of simultaneous CFLOS at multiple sites is very sparse. The satellite data base has several flaws that include variations in pixel size and viewing angle, cloud/no cloud discrimination, and frequency of observation. The Burger modification to Lund's assumption has not been verified. Finally, Lund's estimates do not provide information on the duration of multiple-site CFLOS. On the other hand, Boehm's Sawtooth Wave (BSW) model has been extensively tested against a variety of data sets, and it has been seen to accurately simulate clouds and other meteorological parameters with a root mean square error of approximately 3 percent. The remaining problem, then, is the verification of modeling for CFLOS for multiple sites. As mentioned above, considerable progress has been made along these lines. A model similar to CFARC has been used to simulate minute by minute sunny-lines-of-sight (SLOS)[1]. The spatial and temporal correlations are the same for CFARC and SUNARC. Of prime interest was the duration of cloudy episodes when the sun could not be seen from any of several sites. It was stated that downtime duration statistics obtained from high quality minute by minute sunshine data from the National Climate Data Center were similar both in mean occurrence and variability to that generated by SUNARC. Keeping in mind that we desire a line-of-sight to a satellite rather than the sun and that the sun has an obvious effect on cloud cover, we are nonetheless encouraged by the above results.

Currently, Whole Sky Imager data are being collected at six widely spaced sites. Photos are taken and digitized every 5 min for all sites and every minute for two closely spaced sites. As this data becomes available, direct verification of multiple site CFLOS modeling and correlation statistics becomes possible. These correlation lengths are important for model improvement. Unfortunately, data collection is limited to the daytime. Nighttime model verification must wait for multispectral capability. At least 5 years of data is desired to establish a statistically significant data base. It is important that this data be taken at possible GBL ground sites to establish the possibility of topographical enhancements to CFLOS in certain directions. Interestingly, there are now indications of a high incidence of cloud-free areas on high plateaus surrounded by mountains during the daytime. If this phenomenon is verified, there may be a combination of GBL ground site locations that would yield a lower required number of sites.

Another area of potential improvement in modeling is in the generation of CFLOS duration rather than system outage duration. The reason for this is that the downtime duration statistics generated shows dramatic drops in the number of long duration outages as the number of sites increases. But there are still a large number of short duration outages. For correlated sites it may turn out that there are portions of the year in which the CFLOS durations are relatively short and interrupted by significant outages. It would be important to determine if this were the case in order to prevent system outages during the battle. This is especially true in cases where longer battle times corresponding to midcourse capability become a necessity.

As stated above, another option to achieve availability is to clear the cloud. The system implications may be a reduction in the total number of ground sites. This must be balanced against the cost of the clearing laser facility. There is the possibility that the adaptive optics system for the ground beam director would require enhancement to correct the residual turbulence induced by clearing. There is also the possibility that the natural turbulence in clouds is much higher than in clear air. If this is the case, further optics enhancement would be necessary. A detailed cost trade has yet to be accomplished; however, even if the cost of clearing lasers is higher than proliferation, providing a clearing laser may introduce enough uncertainty into prediction of system availability by any aggressor that it may be well worth deploying cloud clearing subsystems at selected sites.

VI. CONCLUSION

In this report we have discussed the role the DEW SPO at AFSSD has in SDIO's SDS Phase II GBL Element. We have shown the synergism that exits between site selection and space asset constellation and the impact that clouds have on that selection. In particular, once CONUS basing is selected, the most cost-effective constellation consists of HEO monocle relay mirrors in a Molniya orbit and LEO bifocal mission mirrors in a circular orbit. Based on these choices we developed our GBL concept, shown above, and using CFLOS4D determined the required number of ground sites. We have indicated the importance of accurate modeling of multiple site PCFLOS for this case. We have briefly discussed the strides made in verification of the models and anticipate and strongly encourage the use of the Whole Sky Imager data in this process. We recommend continued measurements from these instruments and from satellites to ensure a statistically relevant data base and to locate sites with particularly good topographical enhancements to PCFLOS. Finally, we look forward to integrating the clearing laser concept into our systems studies to determine their effectiveness, cost, and impact on the present GBL concept.

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